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Modern Small Satellites and Its Key Technology

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Abstract In engineering, as in science and the arts, evolutionary processes ultimately lead to simplification and perfection. The rise of modern small satellites shows that space technology is developing in this way.

Because of the remarkable advantages of the small satellites, such as light weight, small size, low cost, high performance and short development time, expect the development of small satellites will bring about a great revolution to satellite applications and satellite technology.

In this paper, the concept and background of small satellites were expounded at first. Secondly the survey of their development was made. Finally, the key technology of small satellites was studied.

Keyword Small satellite Satellite application Development trend
Technology assessment

From 1957 (or 1985) to the end of 1993, the total number of satellites that all countries in the world launched is 4501 (or 1038). Starting in the 70's, the weight of the satellite became heavier and heavier, the technology became more and more complicated. On one hand, it satisfied the objective demand, but on the other hand, there appeared some problems, such as high cost, high risk, long developing time, inability to use the newest technology (such as high performance computers).

The small satellite which appeared near the end of the 80's went back to the status of small size and light weight as in the prime time of the space flight age, but the actual situation has totally changed. Modern small satellite technology will adopt modern new and high technologies in time, greatly enhance the "function density" of the

satellite, employ new design concepts and scientific management methods, thus the modern small satellite will have five remarkable characteristics such as low cost, light weight, small size, high performance and short development time. Because of these remarkable advantages, also because it will exploit new areas of the satellite's application and has potential and considerable benefits, in the future, the development of the small satellite will bring a great revolution in satellite technology and satellite application.

In this paper, at first we will discuss the concept and the background of small satellites, then the survey of their development will be made, finally, we will emphasis on the key technology of the small satellites.

1. The concept of small satellite

If the concept of small satellite is classified into two parts of traditional simple small satellite and modern high performance small satellite (being called small satellite for short), the first part mainly refers to the small satellites that were launched before the 70's, especially in the prime time of spacecraft development. It is also what is called traditional simple satellites. Another part is referred to as the modern small satellites that were developed after the 80's. As for the modern small satellite

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(if there is no special note, it is also called small satellite) there is no exact definition till now that is generally recognized, but the space flight organizations in many countries presented their views and classification methods one after another.

As a relatively common view, the satellite can be classified into huge satellite (heavier than 3.5t), large satellite (heavier than 1.5t), medium satellite (heavier than 500kg), small satellite (lighter than

500kg) according to weight (as shown in figure 1).

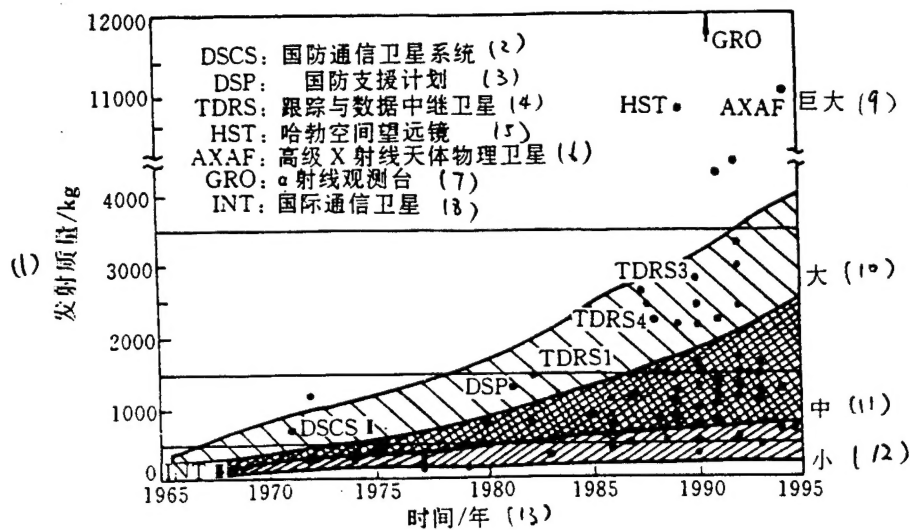


Figure 1. The classification of the satellite's size

- Key:
1. launching weight
 2. DSCS: defense satellite communication system
 3. DSP: defense supporting plan
 4. TDRS: tracking and data relaying satellite
 5. HST: Herber space telescope
 6. AXAF: advanced X ray astrophysics satellite
 7. GRO: Gamma Ray Observing station
 8. INT: international network telecommunication satellite
 9. huge
 10. large
 11. medium
 12. small
 13. time / year

The classification method, which classifies the small satellites as those whose weight is lighter than 500kg, is recognized relatively commonly. The Surrey University in British, known as the small satellite developing pioneer of the world, continued to classify it more thoughtfully as:

- (1) The satellites whose weights are lighter than 500kg are all called small satellites.

(2) The satellites whose weights are between 100kg ~ 500kg are called mini satellites.

(3) The satellites whose weights are between 10kg ~ 100kg are called micro satellites.

(4) The satellites whose weights are lighter than 10kg are called nano satellites, including those whose weights are lighter than 1kg, they are called "nanometer" satellites.

In addition to using weight as the classification criterion of the small satellites, more comprehensive and more exact criteria should be used to define the small satellite concept, those criteria include the following five features:

1) Light weight. It is usually regulated by the carrier rockets that launch those small satellites. Currently there are three kinds of modes to launch the small satellite: (1) Carrying (depend on the mode of the carrier rocket, generally the weight is from dozens of grams to about several hundreds kilograms); (2). One rocket multiple satellites, generally the weight is from dozens of kilograms to 200 ~ 300kg; (3). Cheap and dedicated carrier rockets (such as the Scout, Pegasus, Taurus of the US, the Long Marching No. 1 of China, M-2S-2 of Japan), they can launch small satellites which are heavier than several hundreds of kilograms.

2) Small size. It matches the weight. It depends on the specification of the carrier rocket. For example, it is defined in Japan that the length, width and height of the mini satellite can not exceed 50cm.

3) Low cost. The utilization of cheap launching vehicles, mature and advanced technologies and scientific management means that the cost per kilogram for the small satellite is only a small portion of that for the large satellite (usually $1/2 \sim 1/10$); for a small satellite, the cost is from several millions dollars to less than ten million dollars, for a micro satellite, the cost is less than one million dollars.

4) Short developing time. Generally it takes 1 ~ 2 years.

5) High technical performance of the satellite. Due to the active adoption of the new technologies, the technical performance of the satellite becomes better and better. It is mainly represented by each subsystem itself of the satellite (including structure, power supply, gesture control, on-board computer, temperature control, remote measurement and remote control, propulsion) and

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payload. The subsystems of the satellite show their technology levels by "function density", that is to obtain maximum function for each kilogram weight cost, for example, the function density of the power supply is electricity generating power / kilogram; that of the gesture control is directing precision / kilogram; that of computer is computing speed / kilogram. For the function density of the payload, it has different demands for different applications of a satellite. Direct indicator, for example, time and space resolution is for the remote sensor satellites, communication capacity and channel are for the communication satellites.; Indirect indicator, includes the effective load weight and power per kilogram that a satellite can supply. The criteria to evaluate the satellite's technical performance are main characteristics to distinguish the traditional satellites and the modern small satellites.

These five characteristics of the small satellites are relative, with the advancement of time, they will be enhanced step by step. Currently the most important characteristics of developing the small satellite are light weight, low cost and short developing time. As for the "high technical performance", it will develop and advance step by step by continually adopting the new and high technologies.

2. The background of the small satellites

At the end of the 80's, the small satellite began arising in the

world, moreover, it developed continually, the space flight organizations in many countries paid attention to it. The background of the small satellite's development can be generalized as following:

1) The cost of large satellite is high, the launching cost is expensive. The armament investment was reduced significantly after the cold war, in order to continue the development and application of space technologies, it is required to transfer its military technologies to peace time technologies. Developing the cheap small satellite is a relatively ideal way. Figure 2 shows the reasons for the development of large satellites in the past and the development of the modern small satellites.

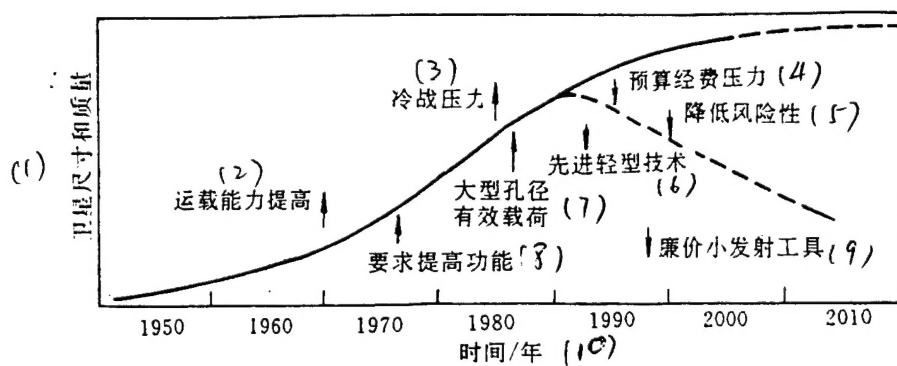


Figure 2. The diagram illustrating the background of the small satellite's development

- Key:
- (1) Satellite size and weight
 - (2) Increasing payload
 - (3) Pressure of the cold war
 - (4) Pressure of the budget
 - (5) Reduce the risk
 - (6) Advanced small satellite technology
 - (7) Large aperture and effective load
 - (8) Demand to enhance function
 - (9) Cheap small launching vehicle
 - (10) Time / year

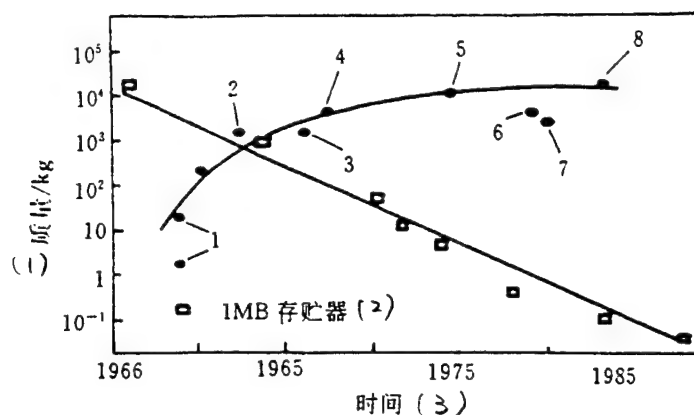
2) The complexity of the large satellites requires longer developing time, and the reliability hardly can reach 100%, and it takes tremendous investment to yield marginal reliability, so the large satellites have higher risk. Figure 2 shows that the low risk is also one of the reasons that cause the development of small satellites.

3) Modern cheap carrier rockets (such as Pegasus, Taurus, and Scout) and carrier launching (such as Ariane rocket) reduce the launching cost greatly. Recently the retired rockets (weapons) are adapted to small satellite launching tool, thus the small satellite's launching cost decreases to less than several thousand dollars per kilogram, or even less. Figure 2 shows that the cheap miniature carrier rocket is also one of the reasons that cause the development of small satellites.

4) The development of new and high technologies makes it possible to develop the small satellite. The new and high technologies include microelectronics technology, computer technology (including software), micro optics and mechanics, light composite material, finish machining, new material, new technology, and so on, especially microelectronics technology, computer technology. Figure 3 shows that, in recent 30 years, the weight of the satellite increased three orders of magnitude, while for 1MB computer memory, it weight decreases four orders of magnitude. If they contrast with each other, the difference is seven orders of magnitude, we can see that the contrast is very

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obvious. At the same time it explains that the miniaturization of satellites and the development of small satellite are the necessary development trend.



Key: (1) weight (2) 1MB memory (3) time

Figure 3. The increase of satellite's weight contrasts with the development of microelectronics technology

1. Pioneer 2. Discoverer 3. Pegasus rocket 4. Orbital astronomic observatory 5. Space laboratory 6. High energy astronomical observatory -3 7. Armada communication satellite
8. Tracking and data relaying satellite - A with up link

5). The military demand. The developing time of small satellites is short, it fits the urgent military demands very well. A quick launching is very suitable for gusty events, it was fully proved in the past Gulf war. Also it is very useful for a future regional or peripheral war.

6). New satellite application demand. For example, for the mobile two-way personal communication and the high resolution in time and space remote sensing satellites, it is very suitable to employ the small satellites group (constellation) on low and medium orbits, because for the former one, the receiving and transmitting power are low, delay is short, the application market is large, for the latter one, it is the most economical, at the same time it can acquire resolution remote sensing information with respect to time and space.

7). The small satellite is very suitable for the task of the scientific experiments and technical demonstration (flight experiment). For the institutes and universities, they can bear the developing cost of the small satellite. So this kind of small satellite is also called "university satellite".

8). It also creates an opportunity for the developing countries to possess satellites and actively participate in space activities.

3. The status of the small satellite's development

The modern small satellite developed at the end of the 80's. Its development can be divided into three stages, the key technologies that each stage employed adapted the three developing stages of the small satellite's subsystems which are shown in table 1.

The first stage is exploring and researching stage, is about from late 80's to the beginning of the 90's. At first the small satellite was used in single missions, simple system, and short term scientific experiments, technical demonstration, and education. In this stage, the main task was trying to apply the high technologies, one successful experience was the employment of the microelectronics technology and high speed computer in the small satellite, another task was to explore how to expand the applications of the small satellite.

In the second stage, the small satellite evolved to a special type of satellites, it was also important complementary part of the large satellite. This stage was about from the beginning of the 90's to the end of the 90's. More small satellites employed new and high technologies, and became actual modern small satellites that had high technical performance, low cost, short developing time.

The third stage will cause the revolution of satellite application and satellite technology. It will debut around the beginning of the 21 century. Because the small satellite introduces a lot of new and high technologies, new design concepts and advanced scientific management methods, in the area of commercial satellites and for the market economy, cheap and

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high performance small satellites will win at last. That is to say,

technically and economically, the small satellite can replace part of the large satellites, at the same time it will cause a important revolution of satellite technology and satellite application.

From 1985 to the beginning of 1994, the small satellites launched which have been officially registered in the world's satellites launching table is near 300 total, in which more than 80% satellites have weighed less than 100kg. It means that employing the micro satellites to undergo small satellite research and application is a characteristic of the small satellite's first developing stage. At the same time we can see that, in the period from 1985 to 1989, each year the number of launched small satellites was about 20 ~ 30, in the period from 1990 to 1993, each year the number of launched small satellites increased to about 30 ~ 40. In 1993, there were 105 satellites being launched all over the world, in which there were 29 small satellites, about 27% of the total amount. Of all those near 300 launched small satellites, more than half were launched by "one rocket with multiple satellites" (about 170), moreover, most of them were launched by the Russian. It has developed to a mature technology, every year it is necessary to launch several practical working satellites (tactical communication satellites).

It is estimated that at the end of the 90's, the number of small satellites launched will increase to 40 ~ 50, the commercial small satellite (such as communication satellites) has approximately a 300 ~ 400 million dollars market each year. After the year 2000, the conservative estimation is that the annual launching of small satellites will be more than 70 ~ 80 each year, approximately 1/2 of the total number of satellites launched. The commercial communication satellites will have approximately several billion dollars market each year. According to the research report recently announced by the American Defense Forecast International, in 2000, the total revenue of the small satellite market will reach approximate 3.6 billion dollars, which increases to nearly twice the current revenue.

According to the stages of the small satellite's development mentioned above, it is going from the first stage to the second stage now. The small satellite's five characteristics were fully shown in the application of the first stage, so it attracted the attention of many countries and entrepreneurs worldwide.

4. The key technologies of the small satellite

The key technologies of the small satellite include: the technologies and devices that each subsystem employs; effective payload; new design concept and scientific management and so on.

Table 1 shows the key technologies of the small satellite's seven subsystems in the above-mentioned three developing stages. In these three developing stages, the first stage employed the technologies now available, the second stage is employing the developing technologies, and the third stage will employ the future technologies (after 2010). The seven subsystems include: structure mechanics gesture control, power supply (power), thermal control, instruction and data processing, remote control and communication, and propulsion subsystem. If we compare and analyze the now available technologies that the first stage employed with the developing technologies that the second stage is employing, we can reach the following conclusions, such as:

1) Structure subsystem. The graphite composite material saves more than 25% that of the aluminum structure in mass alone.

2) Gesture control subsystem. Compared with the ordinary reference unit (such as the earth sensor), the weight of a star sensor decreases $1/2 \sim 1/5$, power consumption decreases 50%; the life span of the magnetic suspension counteraction bearing increases up to $2 \sim 3$ times longer than that of the ordinary bearing.

3) Power supply subsystem. The mass of the gallium arsenic solar battery 15% \sim 25% is smaller than that of the silicon solar battery. The mass of the hydrogen nickel battery is 10% \sim 50% lighter than that of the cadmium nickel battery.

4) Instruction and data processing subsystem. The advanced satellite on-board computer will reduce more than 50% in size, weight and power consumption, but increase the working capacity more than 5 times.

5) Thermal control subsystem. High thermal conduction structures will greatly reduce the complexity and the mass of the passive thermal control.

6) Propulsion subsystem. The graphite twisted chamber is reduced more than 50% in cost and mass to the titanium chambers.

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Table 1. The technological development of the small satellite's subsystems (key technologies)

(1) 分系统	(2) 现有技术	(3) 正在发展的技术 (90年代末)	(4) 未来技术 (2010年)
(5) 结构与机械机构	(6) 铝结构, 爆炸释放装置	(7) 石墨复合材料, 聚氰酸盐树脂连接结构, 低冲击释放装置, 树脂转换模压连接	(8) 高模数纤维, 自动制造与模压, 可膨胀结构部件
(9) 姿态控制	(10) 地球敏感器, 太阳敏感器, 重力梯度杆	(11) 小型化的星跟踪器, 轻型反作用轮, GPS 姿态确定, 主动振动控制	(12) 多功能敏感器, 微型机械装置高密度内连
(13) 电源分系统	(14) 铝制蜂窝板上装硅太阳能电池片, 镍镉电池, 按设计制作的点到点配线 (电缆网)	(15) 展开帆板的石墨层面上装薄的硅太阳能电池片, 镍氢电池, 通用压力电容器, 标准化配线 (电缆网)	(16) 薄膜太阳能电池阵 (a-si, CIS), 可展开柔性太阳能电池阵, 锂-离子电池, 硫化钠电池, 结构中的配线 (电缆网) 埋技术
(17) 热控分系统	(18) 铝结构和折叠结构, 电加热, 双金属恒温器多层绝缘, 热管	(19) 高热传导石墨结构, 由星上计算处理机来控制加热器, 板内嵌装热管	(20) 可展开的辐射器, 超轻型展开装置, 薄的柔性热管
(21) 指令与数据处理分系统	(22) 分布处理的 186 处理器 (0.2MIPS ⁽¹⁾), RS422 接口, 多层印刷电路板, 硬导线互连, 扩展的存储器	(23) 中央处理的 1750A 和 R3000 处理器 (1 - 20MIPS ⁽¹⁾), 1553 数据总线, 母板型底板, 固态记录仪 (2Gbit)	(24) 100 ~ 35MIPS ⁽¹⁾ 的处理器, 1773 光学数据总线, 光学高速数据总线, 多芯片模块, 三维组装 (三维数据打包) 磁盘 (16Gbit), 固态记录仪 (250Gbit)
(25) 遥测跟踪与通信	(26) 分离器件, 波导, 刚性反射器, 偏置馈源	(27) 微波 (毫米波) 集成电路, 固态功率放大器, 薄壳石墨反射器, 可展开的反射器板或网格	(28) 单片微波 (毫米波) 集成电路, 高电子迁移率晶体管, 轻型面板/膜片展开, 嵌入式发射/接收模块
(29) 推进分系统	(30) 单组元 N_2H_4 推进剂, 吹下系统, 钛燃料箱, 管路焊接	(31) 高性能双组元燃料, 双模式系统, 高压系统, 石墨包层铝制燃料箱 (石墨缠绕铝贮箱)	(32) 胶体推进剂, 弹性燃料箱, 柔性管路, 电推进器

注 (1) MIPS——兆指令/秒。(33)

- (1) subsystem
- (2) Current technologies
- (3) Developing technologies (late 90's)
- (4) Future technologies (2010)
- (5) Structure and mechanical framework
- (6) Aluminum structure, explosive release gear
- (7) Graphite composite material, polycyanate resin connection structure, low impact release gear, resin converting mold pressure connection
- (8) High modulus fiber, automate production and formed, expandable structure components
- (9) Gesture control
- (10) earth sensor, solar sensor, gravitational gradient pole

(11) Miniature star tracker, light counteraction bearing, GPS gesture determination, active oscillation control

(12) Multiple function sensor, micro mechanical device high density intraconnection

(13) Power supply subsystem.

(14) Silicon solar battery on the aluminum honeycombed plate, cadmium nickel battery, point to point wire according to the design (cable network)

(15) Thin film silicon solar battery fixed on the graphite layer that unfolds sail plate, hydrogen nickel battery, general pressure battery container, standardized wiring (cable network)

(16) Thin film solar battery array (a-si, CIS), unfoldable soft solar battery array, lithium ion battery, sodium sulfide battery, wire (cable net) imbedding technology in the structure.

(17) Thermal control subsystem

(18) Aluminum structure and folding structure, electrical heating, bimetal thermostat multilayer insulation, heat pipe

(19) High thermal conduction graphite structure, heater is controlled by the satellite on-board computer, heat pipe imbedded in the plate

(20) Unfoldable radiator, ultra light unfolding device, thin soft heat pipe

(21) Instruction and data processing subsystem.

(22) Distributing 186 processor (0.2 MIPS*), RS422 interface, multilayer printed circuit board, hard wire interconnection, expanded memory

(23) Central processing 1750A and R3000 processor (1 ~ 20 MIPS*), 1533 data bus, motherboard type board, solid state recorder (2Gbit)

(24) Processor of 100 ~ 35 MIPS*, 1773 optical data bus, optical high speed data bus, multiple chips module, three dimensional assembled (three dimensional packed) disk (16 G bit), solid state recorder (250 G bit)

(25) Remote measurement, tracking and communication

(26) Separate devices, waveguide, rigid reflector, offset feeding

(27) microwave (millimeter wave) integrated circuit, solid state power amplifier, thin shell graphite reflector, unfoldable reflector or grid

(28) monolithic microwave (millimeter wave) integrated circuit, high electron mobility transistor, light plate / film unfolding, embedding transmitting / receiving module

(29) Propulsion subsystem.

(30) Single unit N_2H_2 propellant, blow down system, titanium fuel tank, tube welding

(31) high performance two unit fuel, two mode system, high pressure system, graphite coated aluminum fuel tank (graphite twisted aluminum chamber)

(32) colloidal propellant, elastic fuel tank, soft tube, electrical propulsion device

Note * MIPS --- million instructions per second

To analyze the mass and cost, we enumerate two small satellites A and B which are currently being developed. Figure 4 shows each subsystems' weight proportion,. From figure 4 we can see that the power supply subsystem makes up the biggest proportion of the whole weight, about 38% ~ 42% (corresponding to satellite A and satellite A), the second biggest proportion is made up by structure, about 22% ~ 29% (corresponding to satellite B and satellite A); the third one is gesture control, about 9% ~ 14% (corresponding to satellite B and satellite A); remote measure and control subsystem and propulsion subsystem each makes up about 10%. Thus we can see that to reduce the total weight, the crucial and the most important work is to start the power supply, structure and gesture control subsystems, because their proportions are big, the effect of cutting weight on the whole satellite is very obvious. Taking the high performance small satellite as example, the weight proportion that the effective load makes up the whole satellite can as big as 60% ~ 70%.

The economic proportion of each subsystems is: the largest economic proportion belongs to gesture control, about 13% ~ 18%; the second largest

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one belongs to the structure, about 10% ~ 15%; the third largest one belongs to the power supply subsystem and remote measurement control and data processing subsystem, each makes up about 7% ~ 13%.

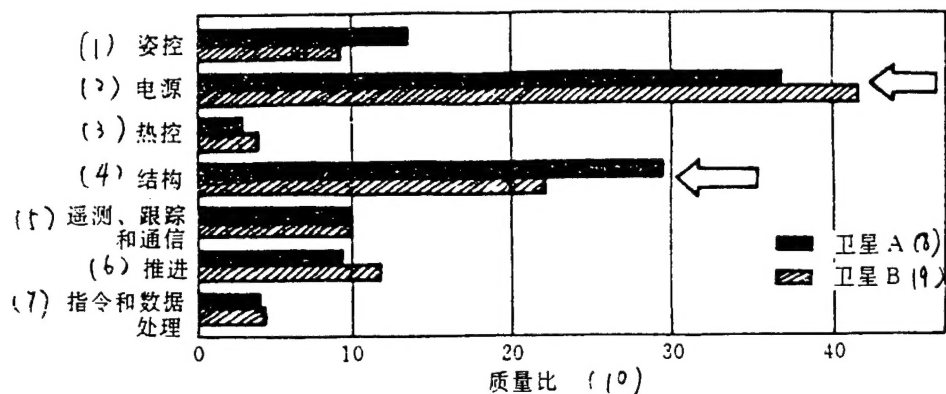


Figure 4. The weight proportion of each subsystem

Key: (1) gesture control (2) power supply (3) thermal control
 (4) structure (5) remote measurement, tracking and communication
 (6) propulsion (7) instruction and data processing (8) satellite A
 (9) satellite B (10) weight proportion

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Author's resume

Lin Lai-Xing, researcher, part-time professor in university, born in May, 1932. He has been engaged in the research of space control and simulation technology. He is the author of "space control technology", "space connection technology" and near one hundred papers.